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BIOMASS & BIOENERGY

Activated carbon from broiler litter: Process description and cost of production ☆

Isabel M. Lima[a,*], *Andrew McAloon*[b], *Akwasi A. Boateng*[b]

[a]*Commodity Utilization Research, USDA-ARS, Southern Regional Research Center, 1100 Robert E. Lee Boulevard, P.O. Box 19687, New Orleans, LA 70179, USA*

[b]*USDA ARS, Eastern Regional Research Center, 600 E. Mermaid Lane, Wyndmoor, PA 19038, USA*

ARTICLE INFO

Article history:
Received 31 May 2006
Received in revised form
30 October 2007
Accepted 24 November 2007
Available online 21 February 2008

Keywords:
Activated carbon
Broiler litter
Copper ion remediation
Cost of production

ABSTRACT

Animal manure continues to represent a significantly large and problematic portion of the US agricultural waste generated yearly. Granular activated carbons made from pelletized poultry litter have been shown to adsorb various positively charged metal ions from laboratory-prepared solutions. The objective of this study was to develop a conceptual capital and operating cost estimate using the Superpro Designer process simulation program. In the study, it was assumed that the activated carbon manufacturing facility obtains the poultry litter from various farmers at a cost of \$5.50 and \$27.50 t^{-1} for transportation. The carbon manufacturing facility processes 20 t of poultry litter per day and converts it into granular activated carbon for a final carbon yield of 21.6% (dry basis). This facility operates continuously, 330 days of the year. Several parameters were incorporated in the study including equipment sizing, capital costs and operating costs, such as labor, utilities, maintenance and equipment depreciation. The largest contributor to the cost of producing the activated carbon is the \$1,200,000 equipment cost of the combined pyrolysis/activation furnace, which contributes about \$0.47 kg^{-1} to the production cost. This study indicates that activated carbon can be produced by this method at a cost of about \$1.44 kg^{-1}.

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1. Introduction

In 2003, the United States produced 8.5 billion broilers and Americans consumed 43.5 kg of broiler meat per capita [1]. In the last 10 years, broiler production increased by 21%, broiler weight increased 12% to 2.35 kg (preliminary data) per bird and broiler per capita consumption increased 26% to an all time high forecasted 46.8 kg of broiler meat per capita for 2006 [1]. This production generated approximately 9 Mt of broiler manure. Most of this residue is land applied as fertilizer and it is commonly sold for about \$5–10 t^{-1}. Associated with excessive land application of broiler manures, is both a public health concern and an environmental threat. The public concern stems generally from odor releases and annoyance to nearby communities, and the latter derives mainly from the potential contamination of air, ground and surface water sources via run-off (mainly phosphorus build-up). Consequently, there is an urgent need to identify new uses for broiler manure and poultry manure in general, specially those uses that result in products of considerable added value. One such opportunity would be to manufacture high value-activated carbons from poultry manure. This value-added

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*Corresponding author. Tel.: +1 504 286 4515; fax: +1 504 286 4419.
E-mail address: imlima@srrc.ars.usda.gov (I.M. Lima).

0961-9534/\$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.biombioe.2007.11.008

approach transforms animal waste into a high-porosity, high-surface-area material that can potentially be used in environmental remediation applications. Our laboratory at the Southern Regional Research Center has been active in developing methods to convert poultry manure to higher value granular activated carbons [2–4]. Specifically, it was demonstrated that poultry manure-based activated carbons are good at adsorbing metal ions commonly found in waste waters from various industrial processes. In our studies, it was observed that the waste-based carbons were as good as or better than commercially available activated carbons at adsorbing metal ions such as Cu^{2+}, Cd^{2+} and Zn^{2+}. Therefore, consideration should be given to process scale-up for the manufacture of such carbons. Scale-up allows costs to be estimated, which will help determine the ultimate marketability of the carbons. The objectives of this investigation were to develop process flow diagrams for the large-scale production of poultry manure-based carbons and to carry out an economic evaluation to estimate the cost to manufacture these carbons.

2. Methodology

A process flow diagram with equipment parameters and mass flows for the production of steam-activated broiler litter-based granular activated carbon was developed using the Superpro Designer process simulation program V5.5 (Intelligen Inc.)™. A process diagram (Fig. 1) was developed along with the equipment. The unit operations include sample storage, milling, pelletizing, pyrolysis/activation, acid washing/water-rinsing, drying, screening and collecting of the final product. After sizing the pertinent equipment, capital and operating cost estimates were then developed from this information, also in Superpro Designer by methods generally used to prepare conceptual cost estimates as described in the Association for the Advancement of Cost Engineering recommended practice Conducting Technical and Economic Evaluations in the Process and Utility Industries (1990) [5].

3. Results and discussion

3.1. *Manufacture of granular steam activated carbon from broiler litter*

For this particular study, a small-to-medium size facility was selected with a daily supply of 20 t of broiler litter per day. Because broiler production is done in concentrated animal feeding operations, abundant supplies of broiler litter are commonly found throughout various areas across the country. Poultry production is particularly concentrated in the Southern and Eastern regions of the US. For this size carbon manufacturing facility, the required daily input of broiler litter can be met by an estimated 40 broiler houses (each one typically houses 25,000 birds).

3.1.1. *Sample preparation*

Broiler litter ($20\,t\,d^{-1}$) is fed into a grinder mill (capacity $833\,kg\,h^{-1}$) and milled to a particle size less than 1 mm. The milled material is then conveyed to a pellet mill (capacity $833\,kg\,h^{-1}$) to produce 4.76 mm × 4.76 mm cylindrical pellets. Milled broiler litter with moisture content below 25% is required for efficient pellet production and therefore for pelletized carbon production. Because this moisture content value is within the expected normal range of moisture found for broiler litter removed from broiler houses, it was not necessary to incorporate a dryer into the system. Within the facility, air movement needs to be controlled to reduce odor and particle emissions. Air management can be achieved by creating a negative pressure within the building. The system

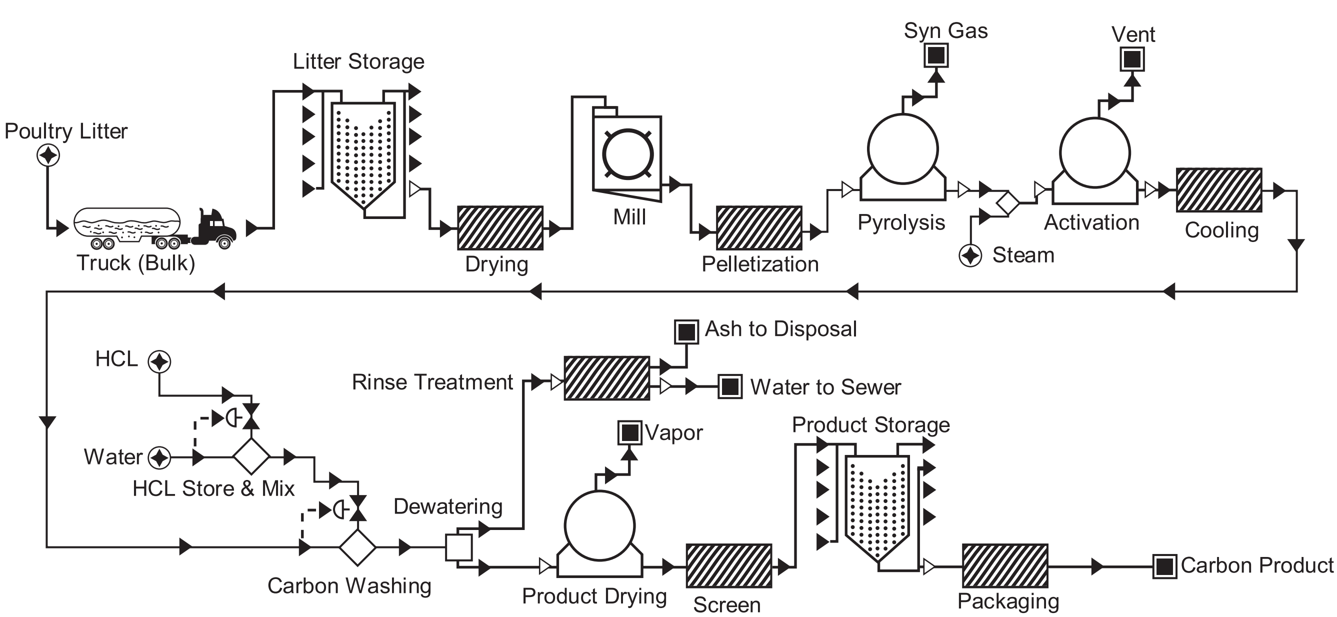

Fig. 1 – Process flow diagram for the production of granular activated carbon from broiler litter.

did not incorporate long-term storage equipment because the facility is to receive daily the amount it needs for processing. Pellets are fed onto a rotary kiln where pyrolysis and physical activation (via steam) occur.

3.1.2. *Pyrolysis/activation*

Pyrolysis is performed at 700 °C under an inert atmosphere for 1 h. After pyrolysis, the produced char goes through an activation step, in order to develop porosity. Activation occurs by heating the chars to 800 °C for 45 min in the presence of steam. When studying various activation strategies, Lima and Marshall [2] found this set of activation conditions to be ideal for copper ion adsorption. Copper ion adsorption efficiency for broiler litter activated under those conditions was 1.2 mmol Cu^{2+} g^{-1} of carbon. Activated carbons are cooled to less than 100 °C before further processing takes place. The above pyrolysis/activation conditions result in an estimated final yield of 21.6% activated carbon on a dry weight basis. Costs were developed assuming a daily input of 20 t of broiler litter, which results in a daily production rate of 4.32 t of activated carbon. Based on these specifications a rotary kiln (retort) system was sized comprised of three stage processes: (i) pyrolysis, (ii) activation coupled with (iii) cooling section. Pyrolysis and activation are carried out in two separate rotary kilns, connected in series to achieve a continuous system. As broiler litter travels through the first kiln, it is charred under inert conditions, and conveyed onto the next rotary kiln where activation takes place. Activation is done by the introduction of steam into the retort at a pre-determined fixed rate. Considerable amounts of heat can potentially be lost in the pyrolysis/activation process as well as off-gases generated during pyrolysis. These synthetic gases can be captured to realize savings in energy. Additional savings can be achieved if equipment can be designed for heat recovery as well as off-gas recycling (for pyrolysis) and/or combustion. A net heating value for pyrolytic gases was reported between 11.1 and 18.5 MJ N m^{-3}, lower than for natural gas (37,100 kJ m^{-3}) [6]. To ensure near complete mixing of the granular pellets which will result in adequate heat transfer, the cross-sectional area of the rotary cylinder occupied by material was chosen as 10% of the cylinder's length [7]. Based on the pellet density of 500 kg m^{-3} and a selected rotational speed of 1 rpm, a 1 m ID was selected. With a residence time of 1 h and a selection of 3° vessel inclination, the pyrolyzer length was selected to be 10 diameters long, i.e., 10 m. Based on the 700 °C temperature specification, high-temperature alloy steel was selected for the pyrolyzer. Based on the load, creep stress at 750 °C was calculated to be 55.2 MPa. A similar sizing criterion was used for the activation section based on the density of the pyrolyzed manure, the char yield and the specified temperature and residence time.

3.1.3. *Post treatment/sample collection*

Once cooled to less than 100 °C, granular activated carbons go through an acid wash step (0.1 M HCl) and water rinse step to neutralize the acid. The acid-wash step is carried out because broiler litter contains significant amounts of inorganic material. The acid wash step is done in 45:1 ratio of volume of acid to initial weight of carbon. The objective of this procedure is to remove loose inorganic material from the activated carbon. Discharged acid-wash water is required to have a pH between 6.5 and 8.5 and therefore would have to be neutralized prior to being released. Due to the basic character of the broiler litter carbons (pH ranging from 7.5 to 8.5), pH of the acid-wash water was found to be closer to the low range for discharge (pH of 6.5), at the end of the acid-wash step. An elemental analysis (unpublished data) performed on both acid-wash and water rinse samples showed leaching of heavy metals to be negligent to non-existent. Especially, none of the metal compounds included in EPA's most recent list of priority pollutants (cadmium, lead and mercury) was found. Nonetheless, the composition of both acid-wash and rinse waters needs to be known for environmental permitting issues. Water treatment would be required and the respective cost would have to be incorporated if these streams fall outside of permissible levels for discharge. An alternative to the acid wash, that avoids the use of an acid, is a simpler water rinse. Preliminary studies revealed that water rinsing was able to remove less inorganic material than the acid wash and rinse. Even so, the adsorption efficiencies for copper ion for the water-rinsed carbons were not significantly different from those found for the acid-rinsed carbons. The preliminary data suggest that water rinsing could be an alternative option to acid wash and rinse, resulting in a lower production cost. The washed and rinsed carbon is sieved to remove excess water. The wet carbon is then dried, screened and bagged. Screening can be tailored based on the customer's choice of what particle size range they require for their specific application. It is expected that fines are generated and, by sieving, these can be separated, collected and bagged to be sold for the powdered carbon market. For this reason, fines were not considered as mass loss in this study. The price per pound for the granular carbon will increase if fines are not used for the powdered carbon market. For the manufacture of sugarcane bagasse-based granular activated carbon, the loss in final product (10 × 40 mesh) sieving was estimated to be 5% [8]. The amount of fines produced depends on the carbon attrition, which is highly related to the hardness of the starting material and the efficiency of the pelletization.

3.2. Cost analysis

3.2.1. *Estimation of equipment and capital costs*

Budgetary quotations were obtained for the two items that make up 80% of the equipment costs (two rotary kilns and the pellet mill). Conceptual cost estimates and allowances were used to determine the remaining equipment charges. Price quotes and size and/or capacity for all equipment are presented in Table 1. Total capital costs were developed from the equipment costs through the application of an installation factor of capital costs to equipment costs [Capital costs = 3 times equipment costs] (Table 2). Excluded from the capital costs were charges for environmental controls, land acquisition and site development, working capital and the cost of capital during construction. Environmental controls can address air emissions during pyrolysis. These costs are variable and also site specific, and are commonly done during the later engineering stages of a project. As mentioned previously, the process can be modified to allow for the elimination of the acid-wash effluent and the reduction in the

Table 1 – Equipment specification and cost

Equipment	Size/ capacity	Units	Cost ($)
Silo/bin for litter holding	26.1	m^3	50,000
Mixer	3877.3	$kg\,h^{-1}$	50,000
Mill	833.0	$kg\,h^{-1}$	17,000
Pelletization	833.0	$kg\,h^{-1}$	250,000
Furnace pyrolysis/ activation	833.0	$kg\,h^{-1}$	1,200,000
Cooling (w/pyrolysis)	242.3	$kg\,h^{-1}$	–
HCl store and mix	3877.3	$kg\,h^{-1}$	50,000
Mixer for carbon washing	4119.6	$kg\,h^{-1}$	25,000
Water rinse	3902.1	$kg\,h^{-1}$	15,000
Dewatering	4119.6	$kg\,h^{-1}$	20,000
Screen/grading	139.9	$kg\,h^{-1}$	25,000
Drier	78.0	$kg\,h^{-1}$	49,000
Silo/bin for carbon storage	30,733.0	m^3	50,000
Packaging	139.9	$kg\,h^{-1}$	25,000
Total			1,776,000

Table 2 – Summary of costs for the production of granular activated carbons from broiler litter

Equipment purchase cost[a]	$1,776,000
Installation	$3,551,000
Total plant direct cost	$5,327,000
Total capital investment	$5,327,000
Operating cost	$1,599,000 yr^{-1}
Production rate	1,108,356 kg of carbon yr^{-1}
Unit production cost	$1.44 kg^{-1} of carbon

[a] Equipment depreciation was calculated on a straight line basis with a 15-year life.

Table 3 – Annual operating costs

	Unit cost	Annual amount	Annual cost ($)	%
Raw material cost				
Water	$0.70 t^{-1}	30.602 kt	21,421	24.3
Poultry litter	$5.5 t^{-1}	6.597 kt	36,285	41.2
HCl	$100 t^{-1}	0.304 kt	30,404	34.5
Total		37.503 kt	88,110	100.0
Litter transportation	$0.028 kg		181,427	
Labor cost				
Plant workforce	$23.47 h^{-1}	8320 h	195,270	70.1
Supervisor	$40.00 h^{-1}	2080 h	83,200	29.9
Total		10,400 h	278,470	100.0
Utilities cost				
Electricity	$50 MWh	3532 MWh	176,606	63.5
Natural gas	$6.3 GJ^{-1}	15,693 GJ	98,868	35.6
CT water	$70 M t	36.000 kt	2520	0.9
Total			277,994	100.0
Facility-dependent			767,000	

Table 4 – Annual operating cost breakdown (%)

Item	Cost (%)
Raw materials	8
Transportation	11
Labor-dependent	18
Facility-dependent	48
Utilities	18

ash amounts in the water rinse effluent, as well as the reutilization of the synthetic gas produced during pyrolysis. If these implementations are put into operation, savings in environmental controls can be realized and can significantly impact the profitability balance of the whole operation. The largest contributor to the cost of producing broiler litter-based activated carbon is the equipment cost of the combined pyrolysis/activation furnace. Estimated equipment cost of $1,200,000 makes up approximately one-third of the total production cost (Table 1).

3.2.2. *Estimation of operating costs*

Operating costs include five general categories, as presented in Table 3: raw material costs, litter transportation costs, labor costs, utilities costs and facility-dependent costs. The activated carbon facility obtains poultry litter from various farmers at an estimated cost of $5.50 t^{-1}. The litter is then transported an average of 10 miles to the processing facility at a cost of $27.50 t^{-1}. The processing facility converts the poultry litter into activated carbon, and this is operated on a continuous basis 24 h a day, 330 days per year. Plant labor is based on four operators, one per shift for a total of 8320 h yr^{-1} at an all inclusive rate of $23.47 h^{-1}. One supervisor for 2080 h yr^{-1} at $40 h^{-1} is also included (Table 3). Utility charges were developed from the estimated electric, natural gas and cooling water requirements of the various equipment items. Approximately four metric tons of water per hour is required as a source of steam for the activation unit and also for carbon washing. In addition to this, plant cooling water is needed for cooling the activated carbons after activation. Natural gas is priced at $6.3 GJ^{-1} and electricity at $0.05 kWh. Facility-dependent costs totaled $767,000 (Table 3) and included depreciation (total capital costs spread over 15 years), maintenance and several overhead charges, which are calculated as a function of the projects' capital cost. Maintenance charges are included at 2% of capital costs, insurance fees at 1% of capital costs and factory expenses at 2% of capital costs. Equipment depreciation is calculated on a straight-line basis with a 15-year life. Table 4 gives a breakdown of the annual operating costs. The largest slice corresponds to the facility-dependent costs. The smallest contribution comes from the raw materials.

Based on a yearly production of 1,108,356 kg of broiler litter-based carbon and an annual production cost of $1,599,000, broiler litter-based carbon would cost $1.44 kg^{-1}. This value compares favorably with other published studies in the literature on the cost to manufacture activated carbons from pecan shells: $2.72 kg^{-1} for steam activation and $2.89 kg^{-1} for phosphoric acid activation [6]; from sugarcane bagasse: $3.12 kg^{-1} for steam activation [8]; from almond shells: $1.54–1.91 kg^{-1} for steam activation, to $2.56–2.93 kg^{-1} for CO_2 activation [9] and $2.45–2.82 kg^{-1} for phosphoric acid activation [10]. If the amount of copper ion adsorbed (1.2 mmol Cu^{2+} g^{-1} of carbon [1]) and the production cost value for that broiler litter-based carbon ($1.44 kg^{-1}) are taken into account, it is possible to estimate an "adsorption cost" value of $1.20 mol^{-1} of Cu^{2+} for these carbons. This value compares very favorably with estimated values of $2.63 mol^{-1} of Cu^{2+} [10] and $3.67 mol^{-1} of Cu^{2+} to $6.74 mol^{-1} of Cu^{2+} [9], for almond shell-based carbons, acid-activated and steam- and carbon dioxide-activated, respectively.

It is important to mention that carbon properties were tested under laboratory conditions. Generally speaking, carbons can be used under wide industrial or municipal settings, which may vary somewhat from ours. Finally, manufacture of steam activated carbons has the ability to produce carbons that have been shown to have superior metal ion adsorption when compared to coal-based commercial carbons [2–4].

4. Conclusions

A study has been done to predict the cost of producing activated carbon from poultry litter by a process developed by the USDA's Agricultural Research Service Southern Regional Research Center. A flow diagram was developed, as well as an estimated fixed capital investment, to come up with a unit cost of production. This study indicates that activated carbon can be produced by this method at a cost of about $1.44 kg^{-1}. The cost to manufacture a kilogram of carbon will depend on the size of the manufacturing plant. Depending on local state regulations, environmental permitting will contribute to the cost of production. It is clear that despite higher initial capital costs, a larger manufacturing plant will be able to produce carbons at a lower cost. Capital costs can also be significantly reduced if used equipment and/or existing installations can be used. If certain modifications are incorporated into the system, such as synthesis gas recovery and reuse as energy source, additional savings could be realized. Because of their ability to adsorb metals, broiler litter-based activated carbons can be better positioned into niche markets for metals remediation. Future studies on the carbon's ability to adsorb other compounds (e.g. organic compounds) will increase the marketability of the product. Existing carbon manufacturing facilities utilize coal as the most common carbon precursor. Besides the fact that it is a non-renewable material, coal costs significantly more than broiler litter, and, unlike litter, coal prices have increased significantly in the past decade. Furthermore, the value of a broiler litter-based carbon manufacturing facility to broiler farmers is high in terms of ability to have a reliable and consistent outlet for a high nitrogenous and phosphorous waste source. This represents a value-adding potential to a problematic waste material.

Acknowledgments

The authors would like to thank Renee Bigner and Bonnie Dillon for the various analyses and Dana Miles for supplying the broiler litter samples.

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